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NUMERICAL SIMULATIONS OF THE DC WIRE PROTOTYPES IN THE LHC FOR ENHANCING THE HL-LHC PERFORMANCES*

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Abstract

For the last 20 years, the compensation of the Beam-Beam Long-Range interactions in colliders using DC wires has been studied. In 2015, in the frame of the HL-LHC project, it has been shown that a compensation of most of the Resonance Driving Terms generated by the BBLR interactions is possible using wires with constraints on their transverse and longitudinal positions. In 2017, an experimental campaign has been launched in the present LHC, with wires installed in sub-optimal positions due to integration constraints. The aim of this paper is therefore to apply the formalism developed for HL-LHC to the LHC case and to compare the experimental results to the numerical tracking studies of the compensation using wires.

INTRODUCTION

In the Large Hadron Collider (LHC) or its future upgrade the High-Luminosity LHC (HL-LHC) [1, 2], the Beam-Beam Long-Range (BBLR) interactions occur only around the Interaction Points (IP), where the two beams share the same vacuum chamber. The $1/r$ asymptotic behavior of the BBLR induced kick (simulations using this approximation were done in [3]) probably originated the idea of a possible compensation using wires, which was first proposed in [4]. Given the high values of the β-functions in this region, with respect to their low values at the IP, the BBLR encounters on the same side of the IP are in phase, while the ones on the opposite side are in anti-phase. This observation first guided the positioning of those wire compensators as presented in [4]. The approach relied on the positioning of the wires in a region where both the horizontal and vertical β-functions were equal, naturally targeting the encounters located in the drift in between the triplets. The potential of those wires has been also demonstrated, at least for round optics, as a path towards compensation of the BBLR interactions for HL-LHC in [5]. It was shown that the Beam-Beam Wire Compensators (BBCWs) could be used to compensate most of the Resonance Driving Terms (RDTs) driven by the BBLR, provided that the wires are located at a specific β aspect ratio. The BBCWs became the so-called HL-LHC Plan B and prototypes were built, installed and tested in 2017 and 2018 [6] with positive results showing the beneficial effect of such a device.

In this paper, tracking results will be shown for the experimental setup used in the LHC. Simulations will also serve as an important tool to better understand the effect of the wires and their sensitivity to the conditions in which they are used. Finally, numerical tracking will show how, from the formalism developed in [5], it is possible to explore a larger space of settings for the BBCWs, and optimize them taking into account possible technical constraints.

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GENERAL METHOD FOR PARTICLE TRACKING IN THE LHC

In order to study the dependency of the Dynamical Aperture (DA) on the wire parameters, MAD-X [7] and SixTrack [8] codes are used. Tracking is performed in the LHC machine, using the novel optics scheme developed in view of HL-LHC: the Achromatic Telescopic Squeezing optics [9]. Table 1 reports the parameters of the simulations. In the Insertion Regions 1 (IR1) and 5 (IR5), both Head-On (HO) collisions and BBLR kicks (21 per IP side) are considered. On the other hand, collisions and long-ranges are neglected in IR2 and IR8 since this configuration corresponds to the experimental conditions [6].

Table 1: Simulation Parameters

Parameter	Symbol	Reference value
Bunch Intensity	N_b	1.15×10^{11} p
β-function at the IP	β^*	30 cm
Half crossing-angle	$\theta_c/2$	150 µrad
Tunes	Q_x, Q_y	62.31, 60.32
Chromaticities	$\xi_{x,y}$	15
Octupole Current	I_{MO}	0 A
Number of turns		10^6

SIMULATION OF THE EXPERIMENTAL SETUP

In the present LHC, four wires have been installed on each side the two high luminosity IPs (IP1 and IP5). The wires are installed in the crossing plane. There are therefore two vertical wires in IR1 and two horizontal ones in IR5. Wires are embedded in the jaws of tertiary collimators [10] of Beam 2 (B2). Both the transverse and the longitudinal positions of the BBCWs are deeply constrained by the collimators' layout and settings. The wire is positioned at 3 mm from the edge of the jaw and the jaw positioning has to respect the hierarchy of the collimation system. Moreover, due to the positioning of the collimators, the left/right symmetry is broken (see Table 2) and the β-aspect ratio - crucial parameter in [5] - is therefore not the prescribed one. Despite this sub-optimal configuration, very positive results, in different

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configurations (reducing the crossing angle, operational scenario...), have been obtained and presented in [6], together with additional details about the experimental setup.

In the experiment, all the wire settings being defined following a similar approach as in [5], and in order to determine the needed current in the wires, two specific RDTs have been targeted. They are the (4,0) and the (0,4) ones, corresponding to the octupolar term, that is the first detuning term induced by the BBLR interactions. The corresponding wire settings used during the experiment (with the collimators half-gap at 5.5 σ_{coll}) are reported in Table 2.

Table 2: Wires settings during the experiments and used for the tracking studies. "RX" ("LX") corresponds to the right (left) side of IRX ($X = 1, 5$).

Wire Compensator	**s from IP [m]**	$I_{w,4004}$ [A]
Wire R1	176.17	350
Wire L1	-145.94	320
Wire R5	150.03	190
Wire L5	-147.94	340

The same configuration has been studied through numerical tracking and results are shown on Figure 1. Comparing the situation without wires (blue line), to the configuration with the wire compensation ON (orange line), a gain of almost 1 σ in minimum DA is observed as well as a gain of 1.2 σ in average DA. This confirms the potential of this device, already observed experimentally.

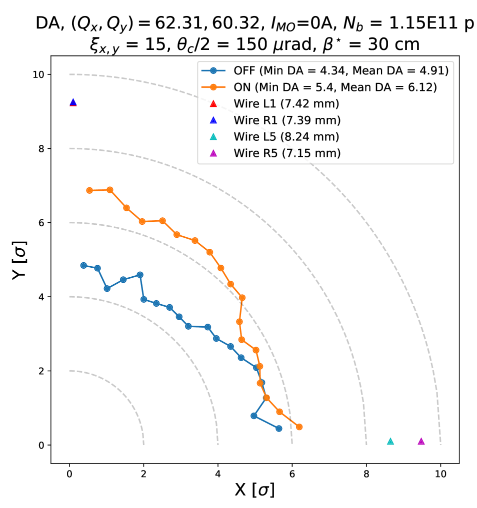

Figure 1: DA with (orange) and without (blue) BBCWs. The wires transverse positions are indicated by the triangle markers.

Moreover, parametric studies can be done in order to further explore the sensitivity of the DA gain to the wires settings. In that respect, Figure 2 shows the dependency of the minimum DA on the beam-wire distances and the wire currents, assuming that the four physical beam-wire distances are the same, as well as the current in the four wires.

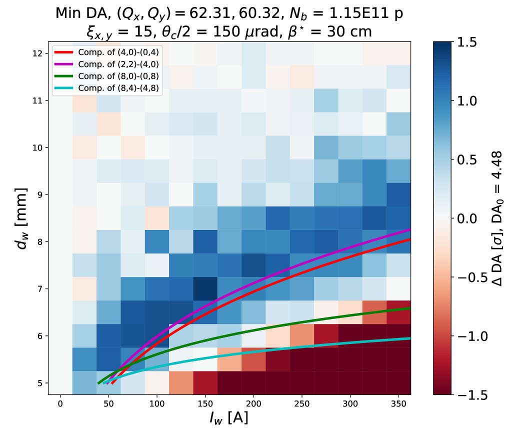

Figure 2: Minimum DA as a function of the beam-wire distance d_w and the wire current I_w. The longitudinal position of the wires is the one in the present LHC. The scale is given with respect to the DA of the machine without wires (4.48 σ). The colored lines represent the function $I_w(d_w)$ needed to compensate a given RDT.

Several wire settings would improve significantly the DA but it seems that the compensation of the octupolar resonances gives the best performances. This flexibility could ease the future wire technical implementation in the ATS round optics scheme, as shown in the HL-LHC case in [11].

TUNE OPTIMIZATION AND WIRES EFFECT

In the previous section, performances of the wires as a function of their settings have been discussed. But the efficiency of the BBCWs depends also on the machine parameters, like the tunes. In [12], it has been shown numerically and experimentally that the DA can be significantly improved by setting the tunes, from their *nominal* values, to the *optimal* ones. Figure 3 shows the dependency of DA on the vertical and horizontal tunes, in a situation without compensation.

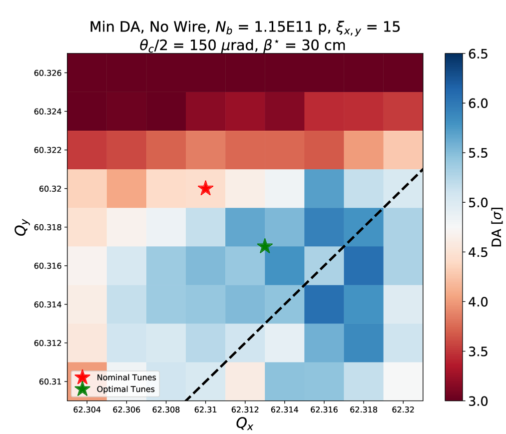

Figure 3: Minimum DA as a function of the vertical and horizontal tunes, without wires.

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The performance of the wire compensators will be affected by the machine parameters as well. The same tune scan can be reproduced with the BBLR compensation, as shown on Figure 4. The wires settings used for this scan are the ones reported in Table 2.

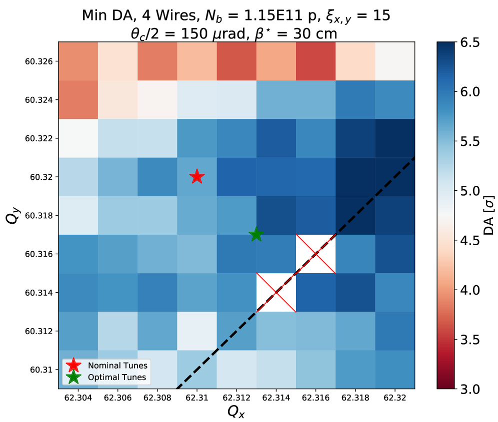

Figure 4: Minimum DA as a function of the vertical and horizontal tunes, with wires ON. The red crosses show the missing points in the study (no DA value).

With the four wires ON, it is clear that the working point area presenting an acceptable DA is significantly enlarged. The DA close to the third-integer resonance is improved, thereby creating a much more comfortable space to accommodate additional non-linear effect or constraints, for instance, for coherent instabilities.

SIMULATION OF THE ANALYTICAL CONFIGURATION

Through this paper it has been shown that the wires can be used in various configurations, keeping a beneficial effect in terms of DA. In the two previous sections, the dependency of the wires' performance on the transverse position, current and tunes has been studied. This section will deal with the impact of the longitudinal position on the compensation performance.

In [5], it is numerically shown that an optimal β aspect ratio $r_w = \beta_x/\beta_y$ at the wires location exists, where compensating two Resonance Driving Terms (RDT) leads to a minimization of most of them. For HL-LHC, parametric studies have been done and results are presented in [11]. In the LHC case, with the wires installed at the optimal aspect ratio equal to ~1.94 or ~0.52, Equation (18) in [5] predicts an optimal compensation of the (4,0)-(6,0) RDTs (and a minimization of most) for the wires transversely located at 5.73 mm from the weak beam, and carrying a current of 105 A.

Performing a parametric study varying the current carried by the wires and the beam-wire distance, one can obtain the results shown in Figure 5. One can indeed observe that the analytical optimum (green star on Figure 5) predicted in [5] brings an improvement of ~1.3 σ DA and that some of the RDT lines (colored lines on Figure 5) are almost crossing at this particular point. This property is not satisfied in the experimental case. Comparing Figure 5 with Figure 2, one can observe that similar performances can be achieved in terms of DA, adjusting the current with the (constrained) transverse position. By placing the wires further from the optimal β aspect ratio, the compensation of most of the RDTs is not possible, and only few can be targeted. Nevertheless, it seems that compensating some of them, and in particular the octupolar ones, is enough to improve significantly the performance of the machine.

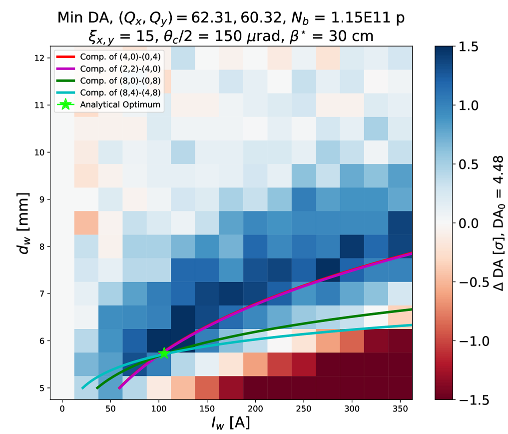

Figure 5: Minimum DA as a function of the beam-wire distance and the current carried by the wires in the LHC. The scale is given with respect to the DA of the machine without wires (4.44 σ).

CONCLUSION

During the last two years it has been shown, through a set a experiments in different configurations, that mitigating the BBLR interaction using DC wires is not only possible, but also promising in view of performances improvement for HL-LHC. To confirm the potential of this device and to optimize its effect, tracking studies have been undertaken in order to determine the parameters the BBCWs are the most sensitive to. In this paper it has been shown that the wires present a great flexibility in terms of transverse and longitudinal positioning, giving good performances in terms of DA even in constrained configurations. Further studies are on-going to understand better the BBLR interactions and their compensation. Numerical studies of the problem will be led for estimating RDTs at all orders, using the PTC module of MAD-X [13] and new experiments with the wires during the Run III of LHC were proposed, in order to gain in experience for the operation of the future high energy colliders with Beam-Beam Wire Compensators.

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